# DESIGN REQUIREMENTS FOR A FIFTH PERCENTILE FEMALE VERSION OF THE THOR ATD

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## ABSTRACT

Requirements have been developed for the design of a fifth percentile female version of the NHTSA THOR male dummy. These include the necessary anthropometric requirements developed by Schneider [1983] and appropriate scaling of dynamic responses of the 50th percentile male THOR frontal crash dummy. The biomechanical requirements include scaled versions of responses for the head, neck, chest and knee. They also include a set of new scaled requirements for the face, kinematic response of the neck in frontal and lateral flexion, impact to the abdomen, responses of the ankle in dorsiflexion/plantarflexion and inversion/eversion, and response of the tibia to dynamic axial heel impact.

## INTRODUCTION

Since the early 1980s, the National Highway Traffic Safety Administration (NHTSA) has supported the development of an advanced frontal crash test dummy with improved biofidelity under frontal impact conditions and with expanded injury assessment capabilities. This has involved extensive research in human anthropometry, biomechanics, and dummy development [Schneider, 1983; Melvin, 1985; Schneider, 1992].

As part of the development effort, a prototype of a frontal crash test dummy, corresponding to a 50th percentile male, was completed in 1996. The principal features of the new anthropomorphic test device (ATD), known as THOR, have been described in White[1996], Rangarajan [1998], and Haffner [2001]. The dummy has been tested extensively at a number of different laboratories and the test results have been reported in a number of different proceedings [Ito, 1998; Hoofman, 1998; Petit, 1999; Shams, 1999].

With the successful development of the THOR ATD, preliminary requirements have been defined for the design of a 5th percentile female dummy based on the data developed for the 50th percentile THOR. The rationale for having several sizes of ATDs has been described by Schneider [1983]. The need for a 5th percentile female dummy in particular arises from the fact that this size is representative of a large fraction of the population who are in automobiles. According to a NCSS study [Schneider, 1983], about 50 percent of automobile drivers and passengers have heights within 4 inches of the height of a 5th percentile female, though their weights are spread over a wider range. Review of the 1995-2001 NASS data files indicated that over 22% of female occupants involved in towaway accidents are 62 inches in stature or less, and over 2.5% of these suffer serious and fatal injuries [Backaitis, 2003]. The 5th percentile female size is thus representative of a significant proportion of occupants who suffer serious injuries. This point has been re-emphasized recently by the studies revealing that a number of deaths and serious injuries have occurred to small statured women because of deploying air bags in out-of-position environments.

The performance requirements for a 5th percentile version of THOR is based on scaling the requirements of the 50th male. The mechanics of this scaling procedure was developed for the conversion of the 50th percentile male Hybrid III to the small female version, and has been detailed in Mertz [1989]. In this paper we will examine the necessary data for obtaining the proper anthropometry and the scaling parameters needed to convert the biomechanical requirements of the THOR-50M to the small female size. In the subsequent discussion, the current 50th percentile male THOR will be denoted by THOR-50M, while the 5th percentile female version will be denoted by THOR-05F.

## 5TH PERCENTILE FEMALE ANTHROPOMETRY

Several studies have examined the geometrical and inertial properties of various sized human subjects [McConville, 1980; Schneider, 1983; Young, 1983]. The principal source of anthropometry for dummies used as vehicle occupants has been the work of Schneider. The McConville study obtained landmarks and body segment definitions for a standing subject, whereas the Schneider study looked at these data for a seated subject. This study developed geometric dimensions and inertial properties and surface landmark locations for three dummy sizes: 50th percentile male, 5th percentile female, and 95th percentile male. For each of the dummy sizes, 25 subjects were used to obtain average and standard deviations for the various data items.

One aspect of the data obtained from the Schneider study was that the shape of the buttocks, pelvis flesh and upper thigh flesh was defined by the interaction with the vehicle seat cushion. The vehicle seat which was modeled was essentially an average geometric shape obtained from different vehicle seat sizes ranging from subcompact to large. In the final phase of the study the actual vehicle seat (with cushion) was replaced with a hard seat which had the surface outline of the compressed seat cushion. Correspondingly, the surface of the upper thigh and buttocks were defined in their compressed shape.

One departure from the normal population statistics, was that the subjects in Schneider's study were selected to be in both the 5th percentile weight and 5th percentile height groups. The general population statistics indicate that an average individual in the 5th percentile height group would have a weight significantly higher than the 5th percentile weight average. The rationale for selecting the height and weight characteristics for the 5th female was to provide extreme data values for both stature and mass in a crash environment to ensure that information obtained from a corresponding dummy would reflect what would happen for both variables. The average stature for the small female from the Schneider study was 151.3 cm (59.6 inch) and the average weight was 46.9 kg (103 lb).

**Body Segmentation**

The THOR 50th percentile male dummy consists of a number of components which are assembled together. The components are generally representative of the corresponding segments of the actual 50th percentile human. The procedure for segmenting the standing adult was developed by McConville [1980]. The procedure was used with some modifications for the seated adult by Schneider [1982]. The standard segments that McConville defined are (along with the approximate joint centers which the planes cut) :

| | |
|---|---|
| Head | -plane cuts approx. at C1/C2 |
| Neck | -between head plane and planes which cut approx. at C7/T1 |
| Thorax | -between neck plane and a plane which cuts through L2/L3 on the spine at back and rib 10 in front |
| Abdomen | -between thorax plane and plane cut through iliocristale landmark on pelvis |
| Pelvis | -between abdomen plane and planes cutting through hip joint representing the thigh/pelvis crease |
| Upper legs | -between pelvis plane (left or right) and plane passing through knee |
| Lower legs | -between bottom upper leg plane and plane cutting through ankle |
| Feet | -segment below bottom of lower leg plane |
| Upper arms | -between plane cutting through shoulder (glenohumeral joint) and elbow |
| Lower arms | -between elbow and wrist |
| Hands | -segment distal to wrist |

The volume which provides the least precise demarcation between separately moving segments is the trunk consisting of the thorax, abdomen and pelvis. The rationale for the segmentation of the thorax and the abdomen was to separate the section of the trunk defined by the bony ribcage (thorax) and the section consisting only of soft tissue (abdomen). The pelvis segment also includes the flesh/skin associated with the pelvic bone. All these three segments may rotate as the individual moves from a standing to a sitting position, so that unique separation planes are difficult to define.

Much of the anthropometry of the THOR-50M segments is based on the measurements quoted by Schneider. One point of departure was the pelvis. The pelvis geometry was based on a model of the mid-size male pelvis developed by Reynolds, et al. [1982]. This model was based on an average pelvis shape derived from 3-D data digitized from a set of human pelvises from the Hamann-Todd collection at the Cleveland Museum of Natural History. This provided more information than the smaller number of landmarks developed in the Schneider study.

Another departure from the segmentation developed by McConville and Schneider is in the shoulder assembly. A simplified version of the human shoulder complex has been modeled within THOR. The dummy has a shoulder segment that has degrees of freedom in fore/aft motion, limited shrug motion, and some flexibility in the clavicular connections to the sternum and the shoulder yoke. At present, there is limited geometrical and inertial data defining the shoulder segment, and more importantly, the compliance characteristics under impact. The method used in THOR was to design some degree of flexibility so that approximately realistic motions could be achieved under belt loading. Again, a scaled version of the THOR-50M shoulder would be a starting point in the development of the THOR-05F shoulder.

Each of the segments, have an estimated mass, moments of inertia, and an orthogonal coordinate frame that is based on anatomical landmarks. For the body in a given configuration (standing or sitting), there will be a coordinate transformation between the laboratory coordinates (within which the whole body is defined) and each of the segment coordinate systems. The importance of the segment coordinate systems arises from the fact that as a body segment moves about a principal joint, the segment coordinate system moves approximately with it.

Figure 1 shows the 5th percentile Advanced Anthropomorphic Test Device (AATD), as developed in the Schneider study, with the lines indicating the segmentation planes. The figure also shows important anthropometric landmarks such as the segment centers of gravity; joint locations; and segment origins.

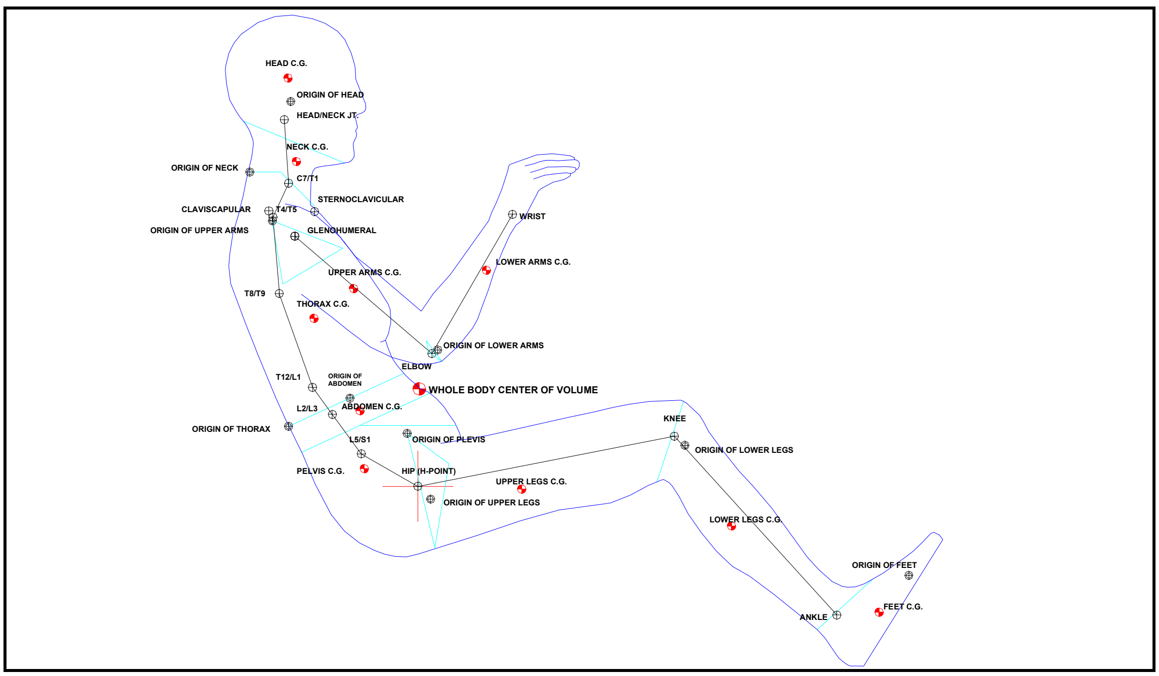


**Figure 1. General layout of the 5th percentile female form [Schneider, 1983].**

### Mass Properties

The masses of the defined segments are derived from estimated segment volumes. The segment volumes are predicted from a set of regression equations based on subject height and weight and certain critical segment dimensions. Assuming a specific gravity of 1.0 for the human segments a corresponding segment mass is derived. The total mass of all the segments is compared with the actual mass for the average subject and a correction factor is derived which is used to multiply the individual uncorrected segment masses to derive the corrected masses. For the 50th percentile male, the average subject mass was .954 of the mass estimated from the segment volumes (with specific gravity of 1.0), and each of segment volumes (in cubic centimeters) was multiplied by this factor to derive the segment masses.

A similar set of regression equations was used to estimate the segment volumes for the 5th percentile female. In this case, assuming a specific gravity of 1.0, the average subject mass was .97 of the total predicted mass derived from the segment volumes. Dempster [1955] suggested that because of the cavities within the thorax, a specific gravity of 1.0 would be an overestimation, and a value of .92 would be more representative. Using this scale factor for the thorax, the estimated mass is then within 1% of the actual 5th percentile average.

The predicted average masses for the segments of a 5th percentile female are taken from Schneider and given in the Table 1.

**Table 1. Body segment mass scales (with density correction)**

| Segment | 50th Male Mass (kg) | 5th Female Mass (kg) | Mass Ratio |
|---|---|---|---|
| Head | 4.54 | 3.70 | 0.82 |
| Neck | 1.05 | .60 | 0.57 |
| Thorax | 21.86 | 11.94 | 0.55 |
| Abdomen | 2.39 | 1.61 | 0.67 |
| Pelvis | 11.52 | 6.98 | 0.61 |
| Upper Arm | 1.87 | 1.12 | 0.60 |
| Lower Arm | 2.22 | 1.14 | 0.51 |
| Upper Leg | 9.00 | 5.91 | 0.66 |
| Lower Leg | 3.90 | 2.36 | 0.61 |
| Foot | 1.06 | .64 | 0.60 |
| Total | 77.46 | 47.17 | 0.61 |

The table provides the ratio of the female segment mass to the male segment mass. This is a rough guide for the scaling that would be involved in reducing the corresponding part in the THOR-50M to the THOR-05F.

It is seen that most segments have the mass ratio, $\lambda_m$ in the range of .60 - .67. The head has a high ratio of .82 while the neck, thorax and the lower arm (with hand) have ratios at the lower end of .50 - .57. These immediately indicate that the same scaling cannot be used for all the segments, and this is reaffirmed by actual landmark measurements done within each segment and presented later in this report.

As has been pointed out, the segmentation in the THOR dummy for the thorax, abdomen, and pelvis is not exactly identical to the definition of the segmentation planes used for the human body by Schneider. Thus the masses in these segments have to be revised to conform to the hardware definitions used in the dummy.

**Range of Motion**

The range of motion signifies the angular amplitude of relatively free motion between the adjacent segments connected at a joint. Schneider [1983] provided range of motion data for the 50th percentile male based on measurements made by a number of authors. No separate measurement of range of motion for females was supplied in that report. Some studies appear to indicate that women have greater mobility than men [Chaffin, 1991]. In a study of 100 men and 100 women in 20 - 50 year age range, women had 5% - 10% greater mobility for the major joints. But, as established data were not available for all the joints of interest, it is recommended that the range of motion data provided by Schneider be maintained as the design goals for the THOR-05F.

**SCALE FACTORS AND BIOMECHANICAL RESPONSE FOR SELECTED SEGMENTS**

The biomechanical response requirements for the THOR-05F was based on suitably scaled versions of the response requirements of the THOR-50M. The latter requirements have been detailed in a separate report to NHTSA [GESAC, 2001]. The procedure for scaling will follow the methodology described by Mertz, et al. [1989]. There is a distinct lack of original data for the 5th female and analytical methods have to be employed to develop the necessary response corridors. For the 5th female, the Task Force formed by the Mechanical Human Simulation Subcommittee of the Human Biomechanics and Simulation Standards Committee of the Society of Automotive Engineers agreed to scale the Hybrid III responses by using the mass and geometric scale factors generated from the ratio of the corresponding elements of the 5th female and the 50th male sizes.

The basic assumption in scaling procedures used in normalizing response data for adults, is that the mass densities and elastic moduli of human tissue (muscle, bone, etc) are about the same for all individuals, irrespective of size or gender. These assumptions are referred to as equal stress/equal velocity scaling. Eppinger [1984] and Mertz [1984] have both developed scaling procedures based on these assumptions.

In general, there will be different length scales along the three different length directions. I.e. there will be scale factors, $\lambda_x$, $\lambda_y$, $\lambda_z$ for the X, Y, and Z directions. Also, the mass scale will be related to the length scales by: $\lambda_m = \lambda_x\lambda_y\lambda_z$ ; assuming that density is the same for the two sizes. The time, acceleration, and force scales may depend on combinations of scales in the three directions.

**Head**

Some of the basic dimensions involved in the head are given in Table 2, based on the data compiled by Schneider.

**Table 2. Principal measures for estimating scaling factors for head**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| Mass (kg) | 4.54 | 3.70 | 0.82 |
| Head Breadth (cm) | 15.8 | 14.5 | 0.92 |
| Head Length (cm) | 19.7 | 18.3 | 0.93 |
| Head Height (cm) | 23.1 | 20.0 | 0.87 |
| Head Circumference (cm) | 57.1 | 53.4 | 0.94 |
| Glabella - Gnathion (cm) | 14.2 | 11.3 | 0.80 |
| O.C. jt - Head C.G. X direction (post-ant) (cm) | 1.7 | .5 | 0.29 |
| O.C. jt - Head C.G. Z direction (inf-sup) (cm) | 5.8 | 5.9 | 1.02 |

It is seen that the measurements in the X-Y plane (length, breadth, circumference) have a higher ratio (.92 - .94) than the vertical dimensions (height, glabella-gnathion) which have a ratio of .80 - .87. The odd measurements are for the separation of the occipital joint and the head C.G. Neither the separation in the X nor the Z direction match the other ratios.

From the above, assuming equal scaling in the X and Y directions, and averaging the three measurements in the X-Y plane and the two measurements in the Z direction:

$$\lambda_x = \lambda_y = .93; \qquad \lambda_z = .84 \tag{1}$$

The weight ratio expressed in terms of the length scaling, is based on the relation (1):

$$\lambda_m = m_s/m_i = \lambda_x\lambda_y\lambda_z \tag{2}$$

where: $m_s$ = mass of 5$^{th}$ percentile female head
$m_i$ = mass of 50$^{th}$ percentile male head

If the scaling ratios are equal in length and breadth ($\lambda_x = \lambda_y$) and different in z:

$$\lambda_m = \lambda_x^2\, \lambda_z = .73 \tag{3}$$

which is significantly less than the mass ratio actually observed.

If we approach the problem from the reverse direction and assuming length ratios are equivalent along all three directions:
$\lambda_z = \lambda_m/\lambda_x^2$

then the length scale becomes:
$\lambda_z = .95$

The $\lambda_z$ value obtained from the mass ratio appears to be consistent with the X-Y length ratios. This indicates that using a common scale for all three directions may be most suitable for the head, but points out the problem of using a simplified approach to predicting dimensions of one size based on a limited number of dimensions from another size. Using the average value for the three directions obtained above, we have: $\lambda_x = \lambda_y = \lambda_z = .94$

NOTE: For the design of the Hybrid III small female head, it was assumed to be geometrically similar to the male, and the scale factors were constant in all directions with a value of: $\lambda_l = .931$, based on scaling the measurements in the X-Y plane. The head weight was then defined by the mass scaling given above in relation (3) with $\lambda_m = .81$.

<u>**Head Biomechanical Response**</u> - The head impact requirements for the THOR-50M are based on the tests performed at Wayne State and UMTRI [GESAC, 2001]. The lower velocity impacts (approx 2.0 m/s impact) are based on the non-fracture tests done at Wayne State by Hodgson [1975]. The original tests were performed by drop testing cadaver heads onto a rigid surface. The response requirement

defined for the male dummy was based on an equivalent impact with a 23.4 kg impactor [Melvin, 1985].

The head/skull impact with a rigid surface of the impactor can be modeled as a spring-mass system. The scaling of such a system is given in Mertz [1989]. Assuming the scaling is the same in x, y, and z this leads to: $\lambda_k = \lambda_x$

The scaling for the maximum acceleration, and force are given by:

$$\lambda_a = \lambda_k^{1/2} / \lambda_m^{1/2} = \lambda_x^{1/2} / \lambda_x^{3/2} = 1/\lambda_x \qquad (4)$$

$$\lambda_F = \lambda_k \lambda_x = \lambda_x^2$$

The principal test environment for the 50th percentile response requirements for head impact, as described by Melvin [1985] is given by:

| | |
|---|---|
| Impactor wt: | 23.4 kg |
| Impact speed: | 2.0 m/s |
| Avg impact force: | 5800 N |
| Avg impact duration: | 3.9 msec |

For the small female, the impactor mass is scaled by: $m_i^{05} = \lambda_m m_i^{50} \approx .82 \times 23.4 = 19.2$ kg

and the scaled force and duration given by:

Avg. impact force = $F^{05} = \lambda_x^2 F^{50} = 5100$ N
Avg. duration = $T^{05} = \lambda_x T^{50} = 3.7$ msec

The scaled force vs duration response is shown in Figure 2.

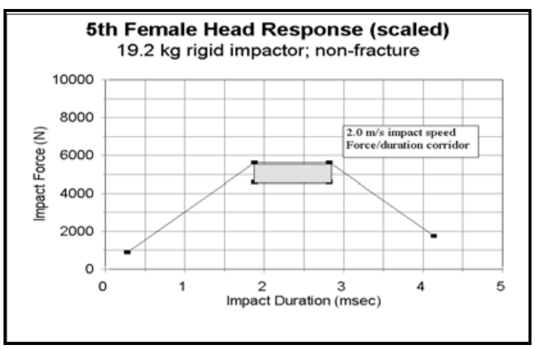


**Figure 2. Scaled head impact response for 5th percentile female.**

**Neck**

The basic mass and linear dimensions for the neck, as measured and reported by Schneider, are given in the following table.

**Table 3. Principal measures for estimating scale factors for neck**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| Neck mass (kg) | 1.05 | .60 | 0.57 |
| Neck Length (anterior) | 8.5 | 8.1 | 0.95 |
| Neck Breadth (mid) | 11.4 | 9.1 | 0.80 |
| Neck Depth (mid) | 11.5 | 9.0 | 0.78 |
| Neck Circumference (mid) | 38.3 | 30.4 | 0.79 |
| Neck Breadth (low) | 12.2 | 10.4 | 0.85 |
| Neck Depth (low) | 11.5 | 9.3 | 0.81 |
| Neck Circumference (low) | 39.3 | 32.2 | 0.82 |
| O.C. jt - C7 | 11.9 | 9.0 | 0.76 |

The linear scales in the X and Y directions (depth, breadth, and circumference) are similar, and averaging the estimates give:

$$\lambda_x = \lambda_y = .81 \qquad (5)$$

There is a discrepancy in the scaling estimate for the Z direction using the neck length and the length between the O.C. joint and the C7 landmark. According to the definition of neck length as given by Schneider, it is obtained by measuring the distance between the compressed tissue under the chin and the suprasternal landmark, (and adding two centimeters to correct for reversing the blades in the anthropometer). It is possible that the compression of the variable thickness tissue may lead to part of the difference in scale factors. Using the relation between the mass scaling and the linear scaling:

$\lambda_m = \lambda_x \lambda_y \lambda_z$ and the values for the mass scale in the table and the X, Y scales given in (5), gives:

$$\lambda_z = .87 \qquad (6)$$

which is in the neighborhood of the average of the neck length and the O.C - C7 length scale factors.

NOTE: For the small female Hybrid III, the Z scale was determined from the scale factor for the erect sitting heights of the two sizes, while the X and Y scales were determined from the mass scaling factor and assuming:

$\lambda_x = \lambda_y = (\lambda_m/\lambda_z)^{1/2}$

In this case, the mass scale was estimated to be .60, while $\lambda_z = .90$ and $\lambda_x = \lambda_y = .82$.

**Neck Biomechanical Response** - For the THOR-50M neck, both kinematic and dynamic requirements were specified. The kinematic requirements specified the motion of the head (relative to T1) for frontal and lateral flexion. A tentative requirement was also defined for motion in extension but will not be discussed here.

There is limited data on the strength of the neck muscles of the female, that provide restitutive torque, during flexion. Lateral flexion responses of 96 volunteers were studied by Schneider et al. [1975]. He found that the females generated about .67 of the isometric lateral pull forces of the males. These are active muscular forces, as opposed to, the passive resistive forces that are thought to be encountered during a normal crash event. If we assume that both forces are proportional to the cross-section area of the muscle fibers, then one would expect from (5), that the female muscle forces should be about .66 that of the male, which corresponds well to above data.

To derive the appropriate scaling for the response for the 5th female, for the kinematic conditions, the basic relations for bending (Bernoulli-Euler formula) are used [Ugural, 1979]:

$$\frac{d\theta}{ds} = \frac{M}{EI} \qquad M = \sigma\frac{I}{y_C} \qquad I = \frac{1}{2}\pi r^4 \tag{7}$$

where: $\theta$ = bending angle
M = moment
I = moment of inertia of cross-section
$y_C$ = distance of farthest neck fiber
r = effective radius of neck

From (7), we have a dimensional estimate for $\theta$:

$$\theta = \frac{\sigma l}{E y_C} \tag{8}$$

where: l = effective length of neck
$\sigma$ = stress on farthest neck fiber
E = effective Young's modulus

Using the equal stress-equal velocity assumption for the two sizes, and the fact that l is measured in the Z dimension and $y_C$ is measured in the X-Y plane:

$$\lambda_\theta = \lambda_z/\lambda_x \qquad \lambda_M = \lambda_x^3 \tag{9}$$

Using (5) and (6) this leads to:

$$\lambda_\theta = 1.07 \qquad \lambda_M = .53 \tag{10}$$

This scale factor will be used to convert both the angle response and the C.G. displacement response in frontal flexion, lateral flexion and extension.

Since the curves given in the THOR-50M biomechanical requirements are time histories, the time values also need to be scaled. The estimate of the time scale is based on the dimensional scaling of the simplified equations describing rotational motion, assuming a resistive torque proportional to angle:

$$I_y\frac{d^2\theta}{dt^2} = M \qquad M \sim \frac{EI}{l}\theta \qquad T \sim \sqrt{\frac{I_y}{(\frac{EI}{l})}} = \sqrt{I_y * \frac{l}{EI}} \qquad I_y = ml^2 \tag{11}$$

where: $I_y$ = moment of inertia for rigid body rotation
l = length of neck
T = time period for rotational oscillations

The relation showing that the moment is proportional to the angle is obtained by integrating the equation in (7). The scale for the time period T is then derived from the scaling for the factors on which it depends:

$$\lambda_T = \sqrt{\frac{\lambda_m \lambda_z^3}{\lambda_x^4}} \tag{12}$$

$$\lambda_T = \frac{\lambda_z^2}{\lambda_x}$$

where the relation: $\lambda_m = \lambda_x\lambda_y\lambda_z = \lambda_x^2\lambda_z$ has been used with the assumption that the scaling in the X and Y directions are the same.

For the scaling factors being used here, this leads to: $\lambda_T = .93$, using the scaling factors in (5) and (6). The following curves show the scaled kinematic and dynamic response curves for the 5th percentile female. To simplify the test procedure, no scaling has been performed on the crash pulse itself, since the delta-V associated with the pulse is assumed to stay constant.

Kinematic Response for 15 G Frontal Flexion - The input pulse for the 15 G level is defined in Figure 3.

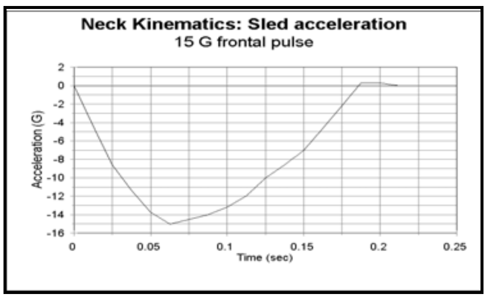


**Figure 3. Input acceleration pulse for 15G neck frontal flexion test.**

The scaled corridor for the head angle rotation for this input is given by Figure 4 and the X and Z displacements of the head C.G. by Figures 5 and 6.

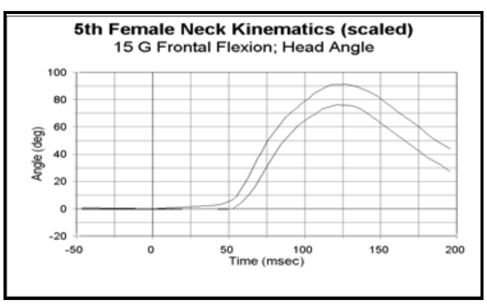


**Figure 4. Scaled head rotation angle corridor for 15 G frontal flexion test.**

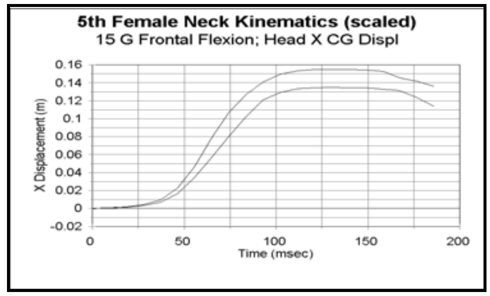


**Figure 5. Scaled head CG X displacement corridor for 15 G frontal flexion.**

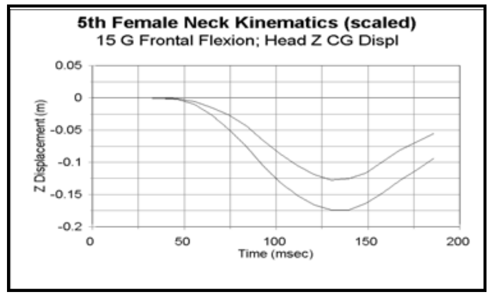


**Figure 6. Scaled head CG Z displacement corridor for 15 G frontal flexion test.**

Kinematic Response for 7 G Lateral Flexion - The sled pulse for testing lateral flexion is given in Figure 7.

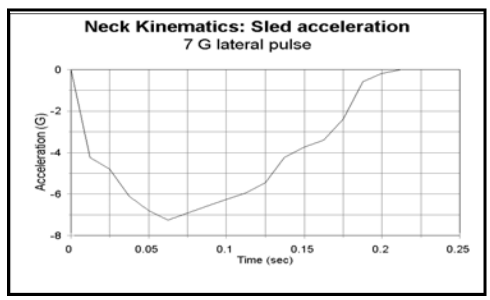


**Figure 7. Input acceleration for 7 G neck lateral flexion test.**

The head angle rotation corridor for lateral flexion is given in Figure 8, and the corridors for the head C.G. displacement given in Figures 9 and 10.

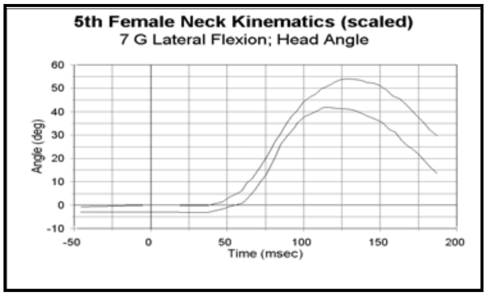


Figure 8.  Scaled head angle rotation corridor for 7 G lateral flexion test.

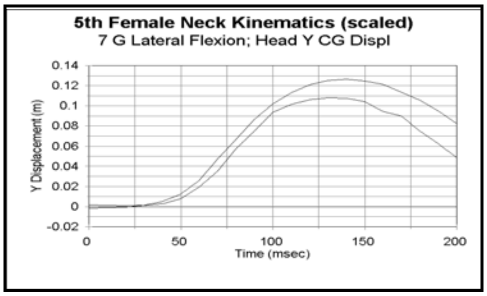


Figure 9.  Scaled head CG Y displacement corridor for 7 G lateral flexion test.

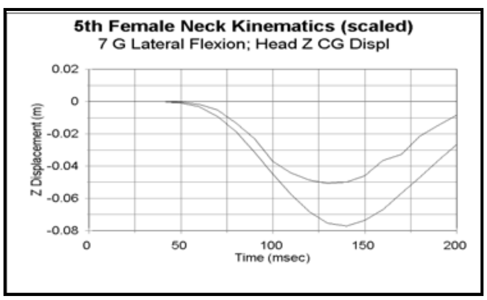


Figure 10.  Scaled head CG Z displacement corridor for 7 G lateral flexion test.

Neck Dynamic Response - The dynamic responses for the 5th percentile female are defined by the scaled version of the data developed by Mertz and Patrick for frontal flexion and extension, and Patrick and Chou for lateral flexion.  The derivation of the scaled corridors has been given in Mertz [1989].  The expected moment vs angle corridors for these are shown in Figures 11 - 13 (measured at the O.C.).

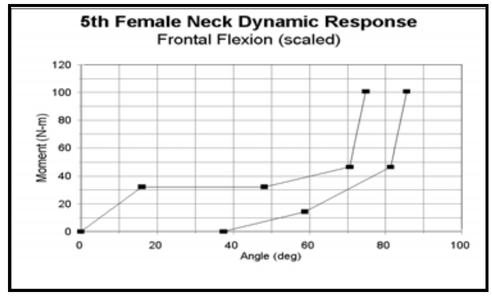


Figure 11.  Scaled moment-angle corridor for frontal flexion.

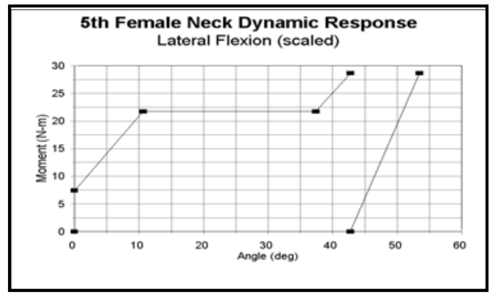


Figure 12.  Scaled moment-angle corridor for lateral flexion.

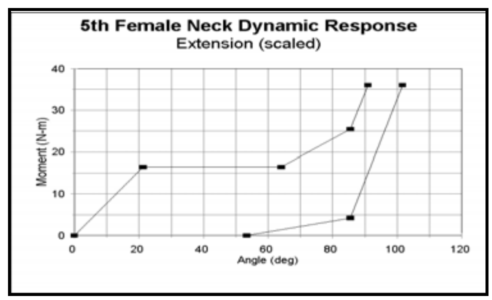


Figure 13.  Scaled moment-angle corridor for extension.

**Spine**

There is only limited biomechanical data at this time to precisely define the response requirements of the two flexible joints in the THOR-50M spine.  Until such data is available, it is suggested that the corresponding elements in the small female dummy be based on the geometric scaling of the current 50th male dummy properties.  The scaling proceeds basically along the same arguments as for the neck, and the relations (7), (8), and (9) are applicable.

Table 4 shows the lengths of the principal spine linkages as presented by Schneider which can be used to develop scaling factors.

**Table 4. Principal measures for estimating scale factors for spine**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| C7 - T4 | 11.2 | 8.4 | 0.75 |
| T4 - T8 | 12.7 | 12.3 | 0.97 |
| T8 - T12 | 11.4 | 12.9 | 1.13 |
| T12 - L2 | 6.6 | 4.7 | 0.71 |
| L2 - L5 | 8.6 | 6.2 | 0.72 |

There is an interesting trend in this case. The upper thoracic spine and the lumbar spine have a scale of about .73, while the lower thoracic spine consisting of the segments between T4 and T12, have an average scaling (in the Z direction) of 1.05, indicating that the female lower thorax is somewhat longer than the overall height scale. The scaling in the X and Y directions will again be assumed the same and based on the scale factors obtained from the horizontal dimensions. For the torso at the level of mid-chest (at level of the nipple), the scale factor is .82. For the lumbar flex joint, the relevant horizontal dimensions also have a scale factor equal to .82.

These scale factors suggest that the upper flex joint should be increased in length by a factor of 1.05, and the cross-section decreased by the factor $\lambda_x^2 = .67$. Similarly, the lower flex joint should be decreased in length (since the lumbar scale factor is less than one) by .72 while the cross section is reduced by .67. Some adjustment may need to be made to ensure that the lumbar joint has enough stiffness to ensure stability of the upper body (torso, neck, head) under normal static standing and sitting conditions.

**Thorax**

A number of measurements were available from the Schneider study which could be applied for estimating the necessary scale factors for the thorax segment. These measurements are shown in Table 5 below. The THOR-50M thorax consists of seven slanted ribs with varying depths and breadths. The layout of the ribcage was to make it closer to the shape of the actual human ribcage and to cover the anterior surface of the ribcage up to the 10th rib (which is the last rib connected to the sternum). Similar geometry will be maintained for the THOR-05F ribcage. Couple of the measurements in Table 5 were taken with the subjects standing. These have been included, since the aim of the THOR-05F design is to develop a dummy that can be set up in different configurations, including standing and sitting.

**Table 5. Principal measures for estimating scale factors for thorax.**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| Thorax mass (kg) | 21.86 | 11.94 | 0.55 |
| *Chest Circum (axilla) | 97.3 | 79.2 | 0.81 |
| *Chest Circum (nipple) | 96.1 | 80.9 | 0.84 |
| Chest Height (nipple) | 55.4 | 51.7 | 0.93 |
| Chest Height (posterior scye) | 57.0 | 55.1 | 0.97 |
| Chest Breadth (axilla) | 30.4 | 26.0 | 0.86 |
| Chest Circum (axilla) | 103.9 | 82.4 | 0.79 |
| Chest Breadth (nipple) | 34.9 | 27.6 | 0.79 |
| Chest Circum (nipple) | 101.0 | 83.3 | 0.82 |
| Chest Circum (10th rib) | 90.9 | 68.9 | 0.76 |

(*from standing measurements)

The scale factor in the X and Y directions are obtained by averaging the measurements in the X-Y plane. Using the above numbers, this leads to $\lambda_x = \lambda_y = .81$. The scale in the Z direction is found from the two measurements of the thorax height in the above table, and from the scale factor for the thoracic spine length from C7 to T12 found from Table 4 given previously. The average factor found from these measurements is: $\lambda_z = .95$. If the thorax mass scale factor is used, and the scale factor for $\lambda_x$ used, then the estimate for $\lambda_z = .84$, which is significantly different. At this time it is suggested that the scale factors obtained from the dimensional scaling be used.

NOTE: For the Hybrid III small female, the following scale factors were used: $\lambda_x = .82$ and $\lambda_z = .90$

<u>**Thoracic Biomechanical Response**</u> - The principal response for the thorax of the THOR-50M is defined by the Kroell test, which involves a mid-sternal impact, with a rigid impactor of 15.2 cm diameter and of mass 23.4 kg, with impact speeds of 4.3 m/s and 6.7 m/s. The response depends on the combined effect of the elastic stiffness of the rib steel, and the velocity dependent stiffness generated from the

damping material attached to the ribs. There is also an effect from the sternal mass which contributes to an inertial resistance to the impact. The standard Kroell corridors give an upper and a lower limit for the expected force-deflection behavior during the course of the impact.

The scaling of the corridor has been described in Mertz [1989]. The scale factor for stiffness is given by: $\lambda_k = \lambda_z$, and the scale factor for deflection by $\lambda_d = \lambda_x$. The scale factor for force is given by: $\lambda_F = \lambda_k \lambda_z = \lambda_x \lambda_z$

In addition, the impactor mass is scaled by the mass scaling factor $\lambda_p = \lambda_m = \lambda_x^2 \lambda_z$.

Using the scale factors: $\lambda_x = .81$, and $\lambda_z = .95$ obtained previously from the direct thorax measurements on 50th male and 5th female volunteers, we have:

$\lambda_F = .77$; $\lambda_x = .81$; $\lambda_p = \lambda_m = .62$

The mass of the impactor is scaled to:
$m_p = \lambda_p(23.4) = 14.5$ kg

NOTE: These factors differ from those developed for the Hybrid III small female. There the factors were: $\lambda_F = .70$; $\lambda_x = .82$; $\lambda_p = .60$. The main difference is in the factor for the force.

Figures 14 and 15 show the scaled Kroell responses at 4.3 m/s and 6.7 m/s for the fifth female.

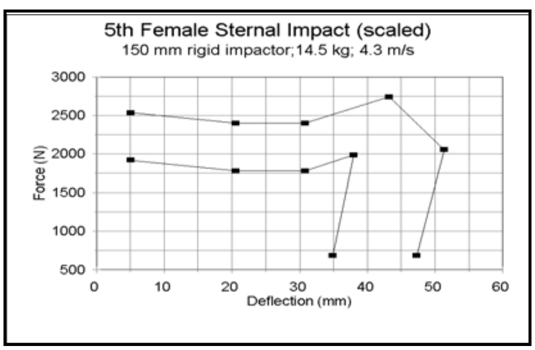


**Figure 14. Scaled force-deflection response of thorax for central disk impact at 4.3 m/s.**

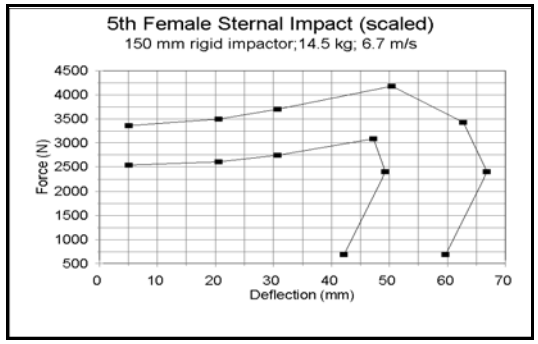


**Figure 15. Scaled force-deflection response of thorax for central disk impact at 6.7 m/s.**

**Abdomen**

The THOR-50M abdomen assembly consists of an upper abdomen which is actually covered by the lower ribcage and a lower abdomen which partially sits within the pelvic cavity. Thus the abdomen segmentation differs from the segmentation offered by Schneider. The abdomen measurements made by him correspond most closely with the lower abdomen in THOR. We will use these measurements to arrive at scaling factors for the THOR-05F abdomen. The relevant measurements made by Schneider, in the X-Y plane, are given in Table 6.

**Table 6. Principal measures for estimating scale factors for abdomen.**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| Abdomen Mass (kg) | 2.39 | 1.61 | 0.67 |
| *Waist Circum | 85.9 | 66.0 | 0.77 |
| Waist Breadth (umbilicus) | 31.4 | 24.7 | 0.79 |
| Waist Depth (umbilicus) | 24.4 | 18.8 | 0.77 |
| Waist Circum (umbilicus) | 90.4 | 70.8 | 0.78 |
| Abdominal Breadth (max) | 32.5 | 27.9 | 0.86 |
| Abdominal Depth (max) | 26.9 | 21.0 | 0.78 |
| Abdominal Circum (max) | 91.3 | 75.4 | 0.83 |

(* from standing measurements)

The measure for abdomen height is obtained from the lumbar spine ratios in Table 4. From these measurements, the average scale factor in the X & Y directions is: $\lambda_x = \lambda_y = .82$. If we use the scale factor in the Z direction, based on the lumbar spine lengths given in Table 4, then: $\lambda_z = .72$. This leads to a mass ratio much less than given above. Conversely, if we use the mass ratio to estimate the scale factor in the Z-direction, then: $\lambda_z = 1.00$. This factor is closer to that used for the thorax and the spine, described previously. Because of the wide divergence for the estimate of $\lambda_z$, it is suggested that the scaling for the thorax be maintained: i.e. $\lambda_z = .95$.

**Abdomen Biomechanical Response** - The THOR-50M abdomen response is scaled to that for a small female by a procedure similar to that for the head and thorax outlined previously. The required response is generated when a 32 kg impactor in the shape of 30 cm rigid bar with a diameter of 25 mm is impacted against the abdomen at 6.1 m/s (at approximately the location of L3). The scaling equations are derived from equations (4) with abdomen values substituted for head. The scaling factors for stiffness, force, and deflection are given by:

$\lambda_k = \lambda_z = .95$
$\lambda_F = \lambda_z\lambda_x = .78$
$\lambda_d = \lambda_x = .82$

The mass of the impactor is scaled to:
$m_p = \lambda_x^2\ \lambda_z(32) = 20.4$ kg

NOTE: Rouhana, et al. [1990] developed a frangible abdomen for the 5th percentile Hybrid III by scaling the 50th male data using a similar procedure. The stiffness scaling factor was $\lambda_k = .87$.

Figure 16 shows the scaled force-deflection response for the lower abdomen.

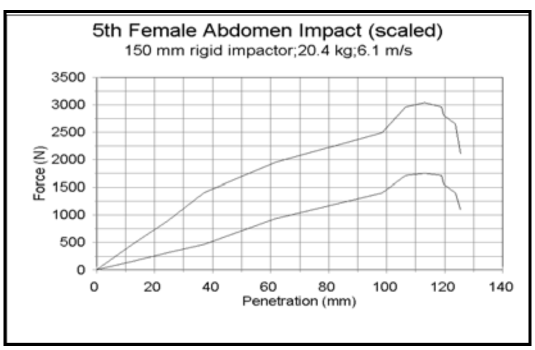


**Figure 16. Scaled force-penetration response for lower abdomen impact with rigid rod at 6.1 m/s.**

**Femur**

The appropriate scaling factors for the femur is obtained from the relevant Schneider data given in Table 7.

**Table 7. Principal measures for estimating scale factors for femur.**

| Measurement | 50th perc | 5th perc | Ratio |
|---|---|---|---|
| Upper Leg Mass (kg) | 9.00 | 5.91 | 0.66 |
| *Troch-Lat. Fem Condyle | 43.5 | 32.9 | 0.76 |
| Troch-Lat. Fem. Condyle | 44.7 | 38.1 | 0.85 |
| Thigh Breadth (upper) | 19.4 | 17.6 | 0.91 |
| Thigh Circum (upper) | 57.9 | 50.1 | 0.87 |
| Thigh Breadth (mid) | 15.5 | 12.5 | 0.81 |
| Thigh Circum (mid) | 50.4 | 42.7 | 0.85 |

(* from standing measurements)

The THOR-50M has a femur assembly with a compliant rubber element inserted proximal to the femur load cell. This element, along with the skin stiffness of the knee, provide the necessary response of the knee-femur-pelvis complex to axial impacts of the femur at the knee. A similar structure is assumed for the small female version of THOR.

From Table 7, there appears to be a decrease in the scale factor in the local X-Y directions for the femur (breadth and circumference). If we use an average of the factors at the upper and mid positions, it leads to: $\lambda_x = \lambda_y = .86$. For the Z direction, we use the mass ratio to obtain it. This gives: $\lambda_z = .89$. This is seen to be much larger than the femur length ratios (trochanter to femur condyle length) in the above table from either the standing or sitting measurements. Again, this points out the problem of variable scaling within a segment. If we use the average scale factor for the thigh in the X-Y directions at the upper thigh location, it gives us: $\lambda_x = \lambda_y = .89$. When this factor is used with the mass scaling, it gives: $\lambda_z = .83$. This appears to be closer to the ratios seen for the femur length above. We will use these latter factors as our preliminary scale factors for the femur. Again, the X, Y, and Z directions correspond to the local axes within the femur, with the Z direction along the length of the femur.

**Femur Biomechanical Response** - The THOR-50M upper leg/femur system consists of two effective springs in series - the spring associated with the knee flesh/skin and the spring corresponding to the compliant femur puck placed at the proximal femur.

The deflection characteristics of both these spring systems are analyzed in the same way as for the head and the abdomen described previously. The response requirement is defined by the force generated by an impactor striking the knee so that the force is directed along the axis of the knee. The impact environment is defined by the mass of the impactor and the impact speed. Impacts can be carried out on the complete dummy, or only on the upper leg/lower leg system with the femur attached rigidly at its proximal end.

In this case, the stiffness is the effective stiffness of the two series springs described previously. For a static case:

$$k = \frac{1}{\frac{1}{k_{skin}} + \frac{1}{k_{fem}}} \tag{13}$$

where: $k_{skin}$ = stiffness of knee skin/flesh
$k_{fem}$ = stiffness of femur puck

Both stiffness have the form:

$$k = E\,A/\,T$$

where: E = elastic modulus
A = effective contact area (either knee or femur puck)
T = effective thickness (either knee or femur puck)

Since both of these stiffnesses are geometrically similar, they are scaled by the same factor. This factor is defined by:

$$\lambda_k = \frac{\lambda_A}{\lambda_T} = \frac{\lambda_x^{\,2}}{\lambda_z} \tag{14}$$

This ratio arises because the contact area is aligned with the local X-Y plane and the thickness with the local Z direction. This is different than the relation obtained for the head and abdomen where the ratio is simplified to: $\lambda_k = \lambda_z$ . It should be noted that these scale factors are along the local X, Y, and Z axes and, as such, X and Y is measured within the cross-section of the leg and Z is measured along the length of the leg.

In this case, the deflection is along the local Z axis, and: $\lambda_d = \lambda_z$. The force is scaled by:

$$\lambda_F = \lambda_k\lambda_d = (\lambda_x^2/\,\lambda_z)\lambda_z = \lambda_x^{\,2}$$

The impactor pendulum is also scaled in the same way as for the chest and abdomen, i.e:

$$\lambda_p = \lambda_x^{\,2}\lambda_z$$

Using the values for $\lambda_x$, $\lambda_z$, we obtain:

$$\lambda_F = .79; \qquad \lambda_p = .66$$

These will be used to scale the 50th male femur response. The standard impactor mass used for knee impacts on the 50th male size was 5 kg. This implies that the equivalent mass for the 5th female should be .66 x 5 = 3.3 kg. For the required THOR-05F femur response, the graph is defined by force and by the equivalent initial energy which is a combination of the reduced mass of the system and the impact velocity. This form allows results for different impactor masses and different impact speeds to be plotted on the same graph.

NOTE: For the Hybrid III small female, the equivalent scaling factors were: $\lambda_F = .73$ and $\lambda_p = .60$.

Figure 17 shows the scaled response of the 5th female to knee impacts.

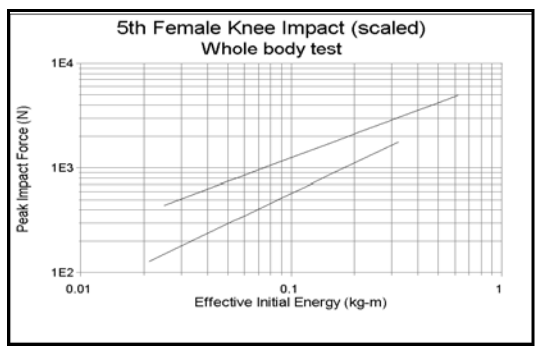


**Figure 17. Scaled knee impact response in whole body configuration for varying impactor mass and velocity.**

<u>**Knee Slider Response**</u> - The sliding response of the tibia relative to the femur is scaled the same way as in the 5th percentile Hybrid III [Mertz, 1989], since this component remained unchanged in THOR-50M.

**Face**

The THOR-50M design includes capability for evaluating likelihood of facial fracture during impact with vehicle components such as steering wheels or side pillars. This capability should be retained in the small female version of THOR. The dimensional data for the face are the same as used for the head and given in Table 2 and we will use the same scale factors as that used for the head. The factors were assumed to be the same in the three directions, with:

$$\lambda_x = \lambda_y = \lambda_z = .94$$

<u>**Face Biomechanical Response**</u> - The facial impact response for the THOR-50M is based on rod and disk impacts performed by Nyquist, et al. [1986], Allsop, et al. [1988], and Melvin and Shee [1989]. The response requirements are in the form of force vs time curves for rod and disk impacts and force vs deflection curves for the rod impact. The response requirements have been summarized by Melvin [1989].

For the rod impact test to the face, a 32 kg impactor is used to strike the face, horizontally, at the level of the zygoma with an impact speed of 3.6 m/s. For the disk impact, a 13 kg impactor is used to hit the whole face at an impact speed of 6.7 m/s.

The procedure for scaling the response and for modifying the impact conditions is the same as given for the head. The force, deflection, and time variables will be scaled by:

$\lambda_F = \lambda_x^2 = .88$
$\lambda_d = .94$
$\lambda_t = \lambda_x = .94$

The pendulum mass should be scaled by:
$\lambda_p = \lambda_m = \lambda_x^3 = .83$. Thus the impactor mass for the rod impact should be reduced to 26.6 kg, and the impactor mass for the disk impact should be reduced to 10.8 kg.

Figures 18 and 19show the scaled responses for the 5th percentile female to face impact with rod and disk.

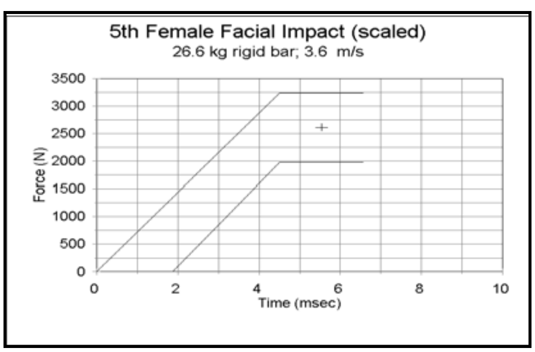


**Figure 18. Scaled force-time response for facial impact with rigid rod to zygomatic region.**

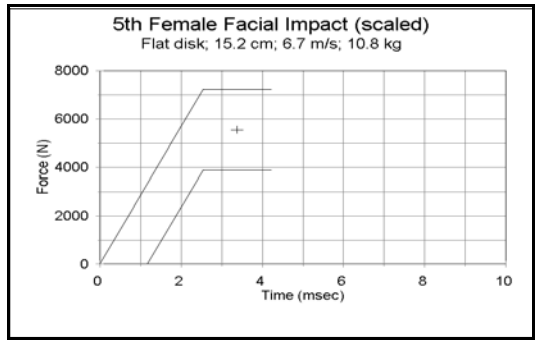


**Figure 19. Scaled force-time response for facial impact with disk.**

**Lower Leg/Ankle/Foot**

The design requirements for the lower leg/ankle/foot of the THOR-05F are based on a scaled version of the THOR-Lx developed for the current THOR dummy [Shams, 1999]. The scaling procedures used for designing these components have been recently described in [Shams, 2002] and will not be presented here.

**DISCUSSION**

The requirements for the biomechanical response of a 5th percentile female scaled from the response requirements of the 50th percentile male THOR dummy have been developed. The requirements for the head, chest, and femur impact follow the procedure described by Mertz [1989] for the 5$^{th}$ percentile female Hybrid III dummy. Also the dynamic response of the neck are similar to that developed for the female Hybrid III. Additional requirements are described for the kinematic response of the neck, impact response of the lower abdomen and impact response of the face. Requirements for the response of the ankle and foot to impact loading have also been developed, but described in a separate paper [Shams, 2002].

The requirements form the basis for designing a biofidelic, 5$^{th}$ percentile female counterpart to the current male THOR dummy. It is expected that such a dummy would improve the capability of assessing the likelihood of injuries in various crash conditions over currently available crash dummies.

**ACKNOWLEDGMENTS**

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